AUTOMATED PRECISION ORBIT DETERMINATION FOR TOPEX/POSEIDON WITH GPS

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A highly automated GPS data processing system for the orbit determination of TOPEX/POSEIDON is described. The orbit is recovered to an estimated accuracy of better than 4 cm in altitude, 6 cm cross track, and 11 cm down track. The RMS postfit residuals on the ionospherically calibrated carrier phase observable are less than 5 mm. The RMS difference over a 4.5-hour overlap period between two 30-hour data arcs is 1 cm in altitude, 5 cm cross track and 4 cm down track. These results can be obtained within two days of onboard GPS data collection. Most of the data processing for a 30-hour arc of GPS data can be performed on a single workstation in less than 6 hours of CPU time. The estimation scenarios are explained; the automated data processing steps are described and means to assess solution quality are discussed.

INTRODUCTION

TOPEX/POSEIDON, a US/French oceanographic mission launched in August 1992, carries two independent tracking systems to provide the operational precise orbit determination needed to meet the mission scientific requirements. These include a French-built one-way Doppler system known as DORIS and a NASA operated laser ranging system. In addition to these operational tracking systems, TOPEX/POSEIDON carries a six-channel GPS receiver capable of making dual-frequency P-code pseudorange and continuous carrier phase measurements-the first of its kind to be placed in Earth orbit. The GPS receiver was placed onboard as a flight experiment to demonstrate the potential of differential GPS tracking for very high precision orbit determination. GPS is the only tracking system capable of providing continuous 3-dimensional tracking of Earth satellites.

The accuracy of TOPEX/POSEIDON orbit determination with GPS measurements has been addressed in several papers (Refs. 1 –3). An orbit accuracy for TOPEX/POSEIDON of better than 4 cm in altitude, 6 cm cross track, and 11 cm down track has been reported (Ref. 2). I Icre wc repeat some of the accuracy analyses with a highly automated processing system, taking into account the

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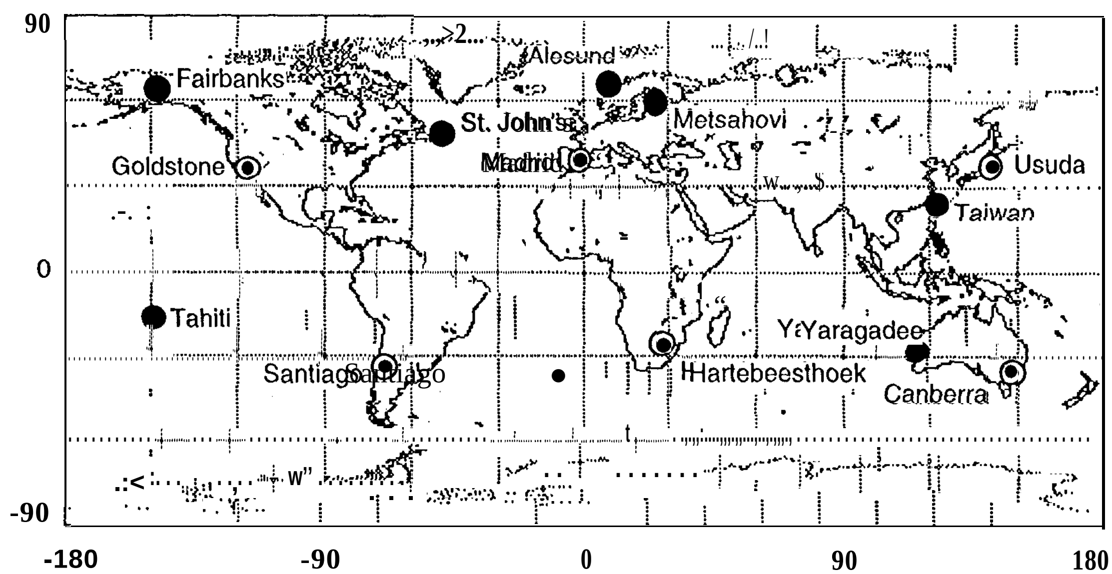
lessons learned in **earlier intensive analysis** (Ref. 1). The core of this **data reduction** system **is the** second generation GPS data processing software systcm, GIPSY/OASIS II, developed at JPL. A detailed description of this software system is given in Refs. 4 and 5. This core software set is driven by a highly automated expert data processing system using various UNIX utilities such as c shell, awk, and seal. It can be set in motion by simply giving the name of the script. It then checks for the availability of data and begins processing when all data are ready. For a typical set of data, no human intervention is requited and the final results appear in the proper data base.

In this paper, we describe a high-level structure and major functions of the automated expert GPS data processing system which yields the high accuracy TOPEX/POSEIDON orbit cited above. in the following sections, the key procedures in the automated data processing arc described; the estimation scenarios are explained and means to assess solution quality are discussed.

AUTOMATED GPS DATA PROCESSING SYSTEM

The GPS demonstration **receiver** (GPSDR) onboard TOPEX/POSEIDON is a dual-frequency, six-channel receiver capable of making continuous carrier phase measurements at a 1 -see interval and P-code pseudorange at a 10-see interval. The data are telemetered back to the JPL processing site via the NASA Tracking and Data Relay Satellite System (TDRSS). The data timetags arc corrected for the gross effects of onboard clock drift and compressed to the more manageable 5-rein normal points according to an algorithm described in Ref. 6. Data collected from a core of 6 Topex ground sites plus an additional 7 sites distributed uniformly about the globe (Fig. 1) are also compressed to the same 5-rein rate. These data are retrieved from this worldwide collection of receivers through a combination of dedicated data transmission lines of NASA's Deep Space Network, internet connections, and phone lines. In addition to the GPS data, nominal values for Earth orientation parameters are obtained by an automated FTP process from the International Earth Rotation Service (IERS); changes in the center of mass of TOPEX/POSEIDON along with special events are obtained from the project via E-mai 1.



Nominal Topex/Poseidon Tracking Sites ● Additional Tracking Sites

Fig. 1. Ground tracking network for TOPEX/POSEIDON using GPS

Fig. 2 is a block diagram of the automated TOPEX/POSEIDON GPS processing system for a single 30-hi arc. On top of this software set wc have built a highly automated expert data processing system using various UNIX utilities such as c shell, awk, and sed. It can be set in motion by simply giving the name of the script. The system is data driven in that it runs autonomously in the background checking various data bases for available data, When sufficient flight and ground network data are available, orbit determination begins. For a typical set of data, no human intervention is required and the final results appear in the proper data base. In addition,

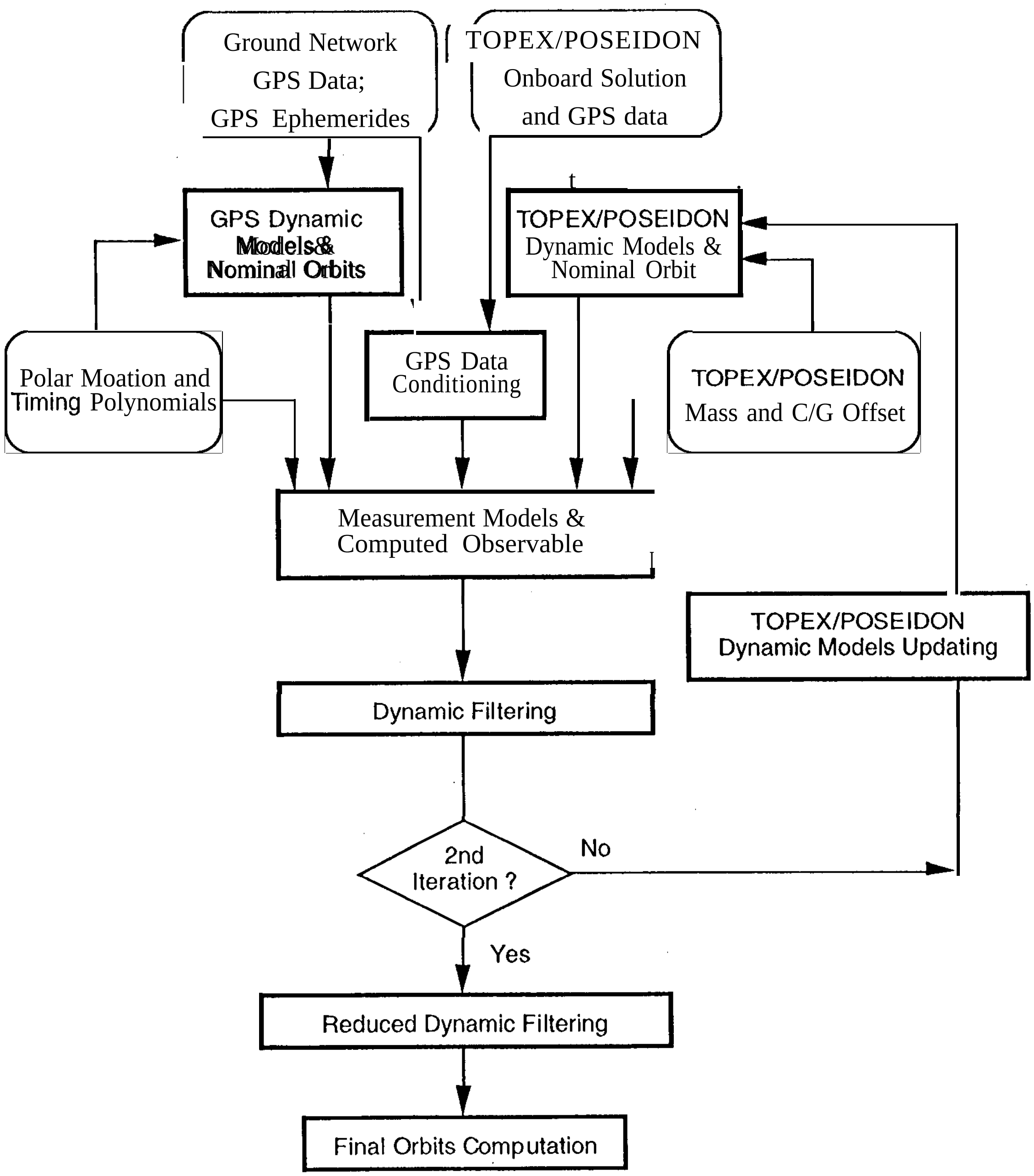


Fig. 2 Block diagram for automated precision **TOPEX/POSEIDON orbit determination with GPS**

various performance statistics are automatically y computed. Currentl y the data are processed in 30-hour chunks, beginning 3 hours before midnight of one day and ending 3 hours after midnight of the next day. Processing is performed by first iterating twice for a dynamic TOPEX/POSEIDON orbit. With the dynamic solution serving as a nominal orbit a final reduced-dynamic orbit is produced (Ref. 7).

Fig. 3 summarizes the required CPU time of the major modules outlined in Fig. 2. The CPU time is dominated by the filter module which performs the parameter adjustment to the observed measurements. Data fetch includes copying data from remote data bases, uncompressing anti reformatting. The maximum disk space required during the data processing is 214 Megabytes.

The following subsections describe the key steps of the automated processing outlined in Fig. 2.

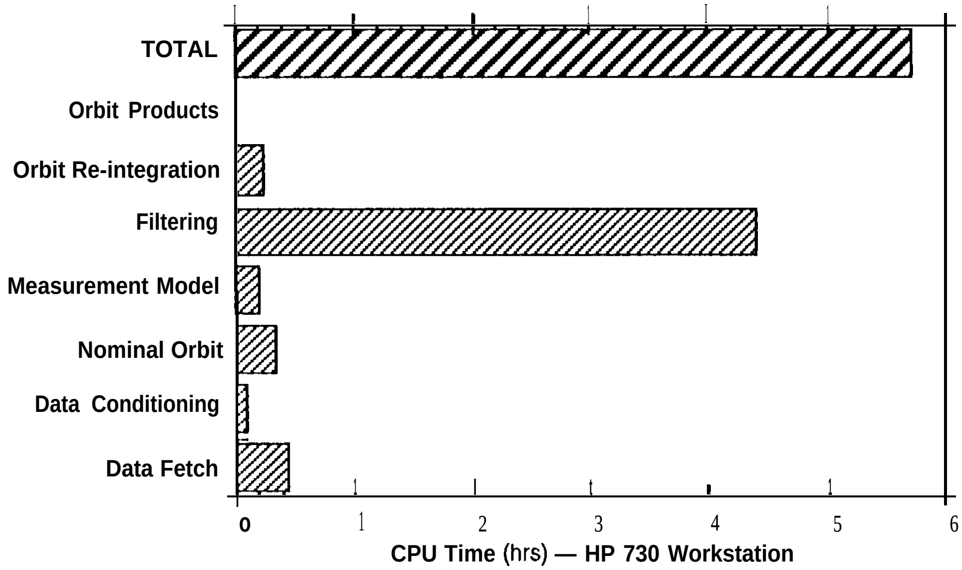


Fig. 3. CPU Time for a 30-Hr Topex/Poseidon Data Arc with 13 Ground Stations

Dynamic Models and Nominal Orbits

GPS broadcast ephemerides and the TOPEX/POSEIDON telemetered onboard orbit solution are used as initial guesses for GPS and TOPEX/POSEIDON epoch states, respectively. These epoch states are integrated using nominal dynamic models to generate the nominal GPS and TOPEX/POSEIDON orbits. Adjustments are made to the epoch states so that the nominal orbits better match the initial orbits and the operation repeats for three iterations. At the end of the iterations the nominal orbits closely resemble the broadcast GPS orbits and the TOPEX/POSEIDON telemetered onboard orbit solution. The dynamic models include, among others, precise GPS specific solar radiation pressure models and TOPEX/POSEIDON specific box-wing macro models for all non-grav dynamics.

In addition to the nominal epoch states for GPS and TOPEX/POSEIDON, variational partial derivatives of orbit elements with respect to epoch states and selected dynamic model parameters are computed using the same precise dynamic models. These variational partial derivatives will be used later in the calculation of measurement partial derivatives with respect to the epoch states of all orbits and the dynamic model parameters to be adjusted in the filtering process.

GPS Data Conditioning

The clock onboard TOPEX/POSEIDON is driven by a crystal oscillator and is let run freely without reset for a long period of time to maintain phase continuity. Hence the timetags of TOPEX/POSEIDON measurements will drift away from the correct time and become non-simultaneous with ground measurements. This will cause significant error upon differencing under GPS Selective Availability (SA), which is normally turned on. To recover data simultaneity, TOPEX/POSEIDON timetags are corrected with a cubic interpolation scheme (Ref. 6) using the high-rate data (1 -see rate for carrier phase and 10-see rate for pseudorange). Carrier phase data editing (detecting and correcting cycle slips) also benefits from such high data rate (ground GPS data are made at 30-sec rate). After editing and timetag correction, the data are compressed to have a uniform 5-rein interval. This lower data rate reduces the following data processing task while maintaining sufficient orbit dynamics.

Measurement Models and Computed Observable

GPS measurements and their partial derivatives with respect to parameters to be adjusted later in the filtering process are computed in this module using precise earth models and dynamic models. Earth models are calculated locally while the dynamic models are contained in the variational partial derivatives calculated in the Dynamic Models and Nominal Orbit step above. Compressed GPS measurements are corrected for antenna phase variation as a function of azimuth and elevation, and for dry tropospheric delays. Prefit residuals of all GPS measurements are also computed by taking the difference between the compressed GPS measurements (the observed values) and the nominal measurements (the computed values). These "O minus C" residuals, instead of the actual GPS measurements, are the data to bc used in the filtering process for parameter estimation. This is essential for keeping the otherwise nonlinear estimation process within a linear regime as the nominal orbits approach the true orbits, resulting in low residuals.

Dynamic Filtering

The epoch states of TOPEX/POSEIDON and all GPS satellites are adjusted together with other parameters as listed in Table 1. In this dynamic filtering, the TOPEX/POSEIDON orbit is adjusted relying fully on available dynamic models. In other words, no TOPEX/POSEIDON dynamics arc treated as process-noise parameters. Two-dimensional (cross track and down track) empirical forces are adjusted to absorb the gross effects of mismodeled forces on TOPEX/POSEIDON. These empirical forces, the magnitudes of which are adjusted as constant parameters, include a constant force and two (sine and cosine) 1- and 2-cycle-per-rev forces. The radial components of these empirical forces are not adjusted due to their high correlation with the adjustment of the TOPEX/POSEIDON radial antenna phase center offset. The robustness of the GPS data allows us to set loose constraints on TOPEX/POSEIDON epoch states and the empirical forces. All GPS and receiver clocks, except one station which is treated as reference, are estimated as a white-noise process with a loose constraint. The reference clock is autonomously selected, among a list of six stations which are known to have stable clocks, based on continuity in GPS observation over the entire 30-hr data arc being processed. Such continuity is important for a stable, consistent orbit solution.

Dynamic Model Updating

The deviation of the initial nominal TOPEX/POSEIDON orbit from the true orbit and the effects of mismodeled forces on TOPEX/POSEIDON are in general large enough to keep the estimation process

TABLE 1. ESTIMATION SCENARIO FOR DYNAMIC FILTERING OF TOPEX/POSEIDON ORBIT

Data Type	Data Weight
Ground Carrier Phase	1 cm
Ground Pseudorange	1 m
T/P Carrier Phase	2 cm
T/P Pseudorange	3 m

(all parameters are treated as constants unless otherwise specified)

Estimated Parameters	Parametrization	constraint
T/P Epoch State	3-D epoch position 3-D epoch velocity	1 km 10 cm/s
T/P Empirical forces (cross track & down track)	constant 1-& 2-cycle-per-rev	1 mm/s^2 1 mm/s^2
T/P Antenna Phase Center Offset	radial	5 m
GPS States	3-D epoch position 3-D epoch velocity	1 km 1 cm/s
GPS Solar Radiation Pressure	*constant:*	
	solar pressure scale factor Y-bias	100% 2x 10^{-3} μm/s^2
	process-noise:	T_u = 1 hrs; τ = 4 hrs
	X and Z scaling factor Y-bias	10% 10^{-4} μm/s^2
Non-Fiducial Station Location	ECEF rectangular coordinates	1 km
Tropospheric delay	random-walk zenith delay	50 cm; 0.17 mm/s$^{1/2}$
Pole Position	X and Y pole	5 m
Pole Position Rate	X and Y pole rate	1 m/day
UT1 – UTC Rate	constant	100 s/day
Carrier Phase Biases	constant over a continuous pass	3x10^5 km
GPS and Receiver Clocks	white-noise	1 sec

away from linear regime. Hence, the parameter estimates are rather inaccurate after the first filtering process. However, this can be improved by updating the nominal models with the estimated values. The nominal orbit and dynamic models are progressively improved with each iteration. Two iterations are sufficient for the TOPEX/POSEIDON orbit solution to converge to a stable solution.

Reduced-Dynamic Filtering

The solar radiation pressure and other dynamics on TOPEX/POSEIDON are complicated forces. Although the gross effects of these complicated forces can be modeled in terms of empirical forces, deviations do exist, This prevents the converged dynamic solution of TOPEX/POSEIDON orbit from approaching the true orbit as closely as the data strength will permit. To remedy this, a final, reduced-dynamic filtering process is performed to re-adjust the orbit and all other parameters except for the empirical constant and 1- and 2-cycle-per-rev acceleration parameters for TOPEX/POSEIDON. In this reduced-dynamic filtering, the carrier phase data weights on the flight data are tightened to 1 cm; the empirical forces and the antenna phase center offset are held fixed; and a 3-D process-noise force with constrained uncertainty and correlation from one time to the next, as listed in Table 2, is adjusted. Due to its flexibility in time variation, the process-noise force can closely trace the residual mismodeled dynamics; hence, the resulting orbit solution is less affected by such mismodeled dynamics and better approaches the true orbit. This reduced-dynamic adjustment is only possible with a data type such as GPS that provides 3-D geometric information nearl y continuously.

TABLE 2. CONSTRAINTS ON 3-D PROCESS-NOISE FORCE REPLACING EMPIRICAL FORCES FOR REDUCED-DYNAMIC FILTERING

Component	a priori σ	Steady-State σ	Correlation Time
radial	0.01 $\mu m/s^2$	0.01 $\mu m/s^2$	15 minutes
cross track and down track	0.02 $\mu m/s^2$	0.02 $\mu m/s^2$	15 minutes

To illustrate how reduced-dynamic filtering recovers a precise TOPEX/POSEIDON orbit with mismodeled dynamics, the following experiment was performed. First, both dynamic and reduced-dynamic TOPEX/POSEIDON orbit solutions were computed using as the nominal model a precise gravity model, JGM-2 (Ref. 8), which had been refined using fifteen 10-day cycles of TOPEX/POSEIDON DORIS and laser ranging data. The two orbit solutions agree to about 3 cm RMS in altitude, which is consistent with the expected uncertainty of the JGM-2 model. Next, the process was repeated using an earlier, less accurate gravity model, GEM-T 1 (Ref. 9). The dynamic orbit solution now differs from that with the precise gravity model by about 25 cm RMS, as shown in Fig. 4(a). This is, again, consistent with the GEM-T 1 model uncertain y. The reduced-dynamic solutions with the precise and the degraded gravity models differ by only 7 cm RMS, as shown in Fig. 4(b), demonstrating the insensitivity of reduced-dynamic orbits to mismodeled dynamics. We believe the residual 7-cm RMS difference for this test can be reduced with improvements of the

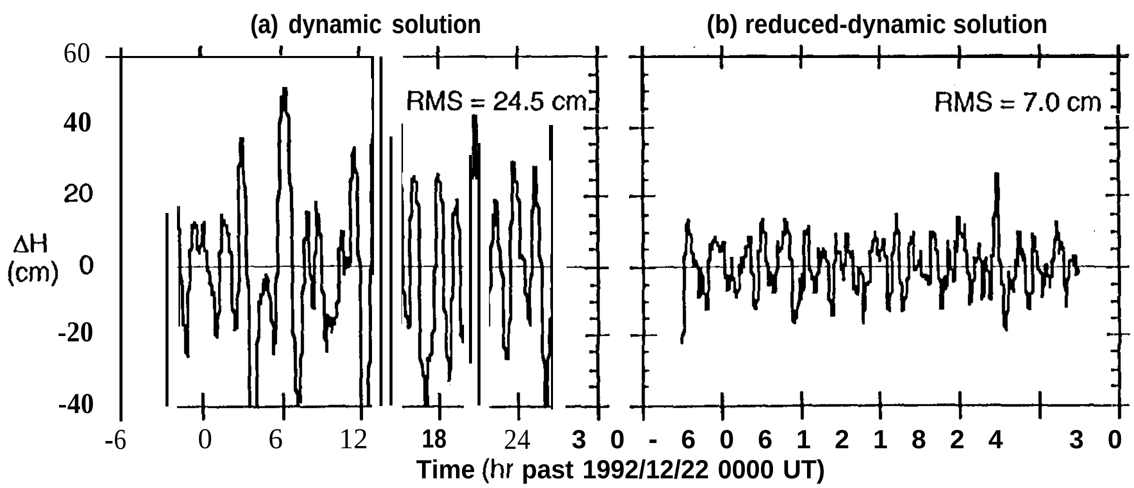


Fig. 4. Differences in orbits computed with degraded gravity model (GEM-T1) and with accurate gravity model (JGM-2)

receiver and with a fuller GPS constellation. The experiment was conducted with data taken on December 22, 1992 when the GPS constellat ion was not full; thus there were frequently t imes when some of the 6 channels of the TOPEX/POSEIDON GPS receiver were not tracking GPS satellites. Although almost all of the information content for the orbit is currently in the carrier phase data type, the receiver's p-code performance can be improved to the point where it will contribute. information in the reduced-dynamic solution.

Final Orbit Confutation

After the reduced-dynamic filtering, the solution of the TOPEX/POSEIDON orbit is mapped to a current-state orbit solution every 60 seconds within the data arc. From this, a variety of orbit interfaces are generated, and in particular the TOPEX/POSEIDON Precision Orbit Ephemeris (POE) file. This current-state orbit solution is used for the assessment of orbit quality in the following section.

ASSESSMENT OF ORBIT QUALITY

The quality of the recovered TOPEX/POSEIDON orbit is assessed in **several ways. These include** postfit residuals, orbit agreement in overlap period, and comparison with orbits inferred from other tracking data types (NASA's laser ranging and French DORIS Doppler system). The following subsections discuss these assessments.

Postfit Residuals

As one of the quality checks, the postfit residuals on the ionospherically calibrated carrier phase and pseudorange measurements over the full arc are examined. Anomalous data points are automatically detected and removed. In general, the phase residuals have an RMS value of less than 5 mm; and the pseudorange residuals have an RMS value of less than 70 cm. These values are nearly equal to, respectively, the phase data noise and the combined pseudorange data noise and multipath error. This implies no outrageous mismodeling in the estimation process. GPS data are in general of high quality; only 0,01% of data are detected as anomalous and automatically removed from the filtered solution.

Orbit Overlap

As mentioned above, GPS data are processed in 30-hour chunks, beginning 3 hours before midnight of one day and ending 3 hours after midnight of the next day. Between two consecutive days there is a 6-hr overlap period, Although part of the data used are common in yielding the two orbit solutions in this overlap period, they are believed to be quite uncorrelated due to independent determination of GPS orbit and dynamics, and ground station locations. Therefore, the orbit agreement in the overlap is a good indication of the orbit quality.

To avoid the "edge effects" commonly encountered with orbit determination using a long data arc, 45-min segments from each end of the two solutions are omitted. This leaves a 4.5-hr overlap between two consecutive days for agreement analysis, as shown in Fig. 5. A sample of the orbit difference during the 4.5-hour overlap is shown in Fig. 6. The RMS difference is 0.88 cm in altitude, 5.70 cm cross track and 3.44 cm down track. Fig, 7 shows the RMS overlap agreement in altitude for twelve complete 10-day cycles. The RMS agreement is consistently below 2 cm, with an average of about 1 cm. These results with reduced-dynamic filtering are consistently better than

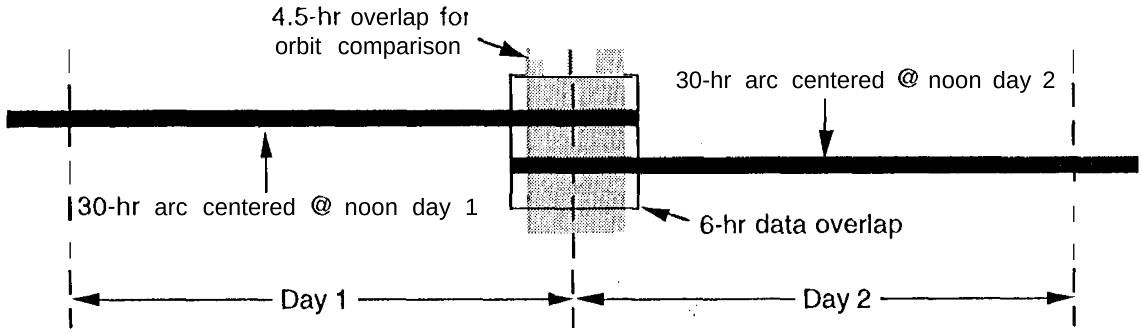


Fig. S. Overlapping data arcs and orbit solutions

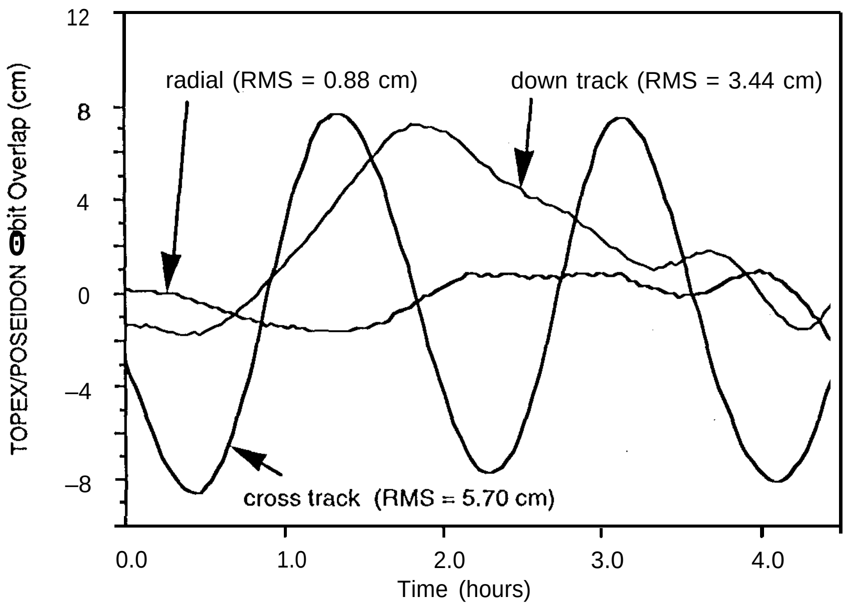


Fig. 6. Comparison of overlapping TOPEX/POSEIDON orbit solutions

the dynamic filtering results which have an altitude overlap difference as high as 5 cm with an RMS value of about 3 cm.

Comparison with DORIS and Laser Ranging

As mentioned earlier, GPS is an experimental tracking system for TOPEX/POSEIDON; two ground-based systems, NASA's laser ranging and the French DORIS Doppler tracking, were implemented as the operational tracking systems. 'I'he three tracking systems differ from one another in data coverage as well as in geometrical strength. Hence, TOPEX/POSEIDON orbit solutions determined with data from these tracking systems are expected to have different error characteristics. A comparison between these solutions provides an independent, reliable stringent test on all tracking systems: good orbit agreement between any pair of these tracking systems implies good accuracy for both.

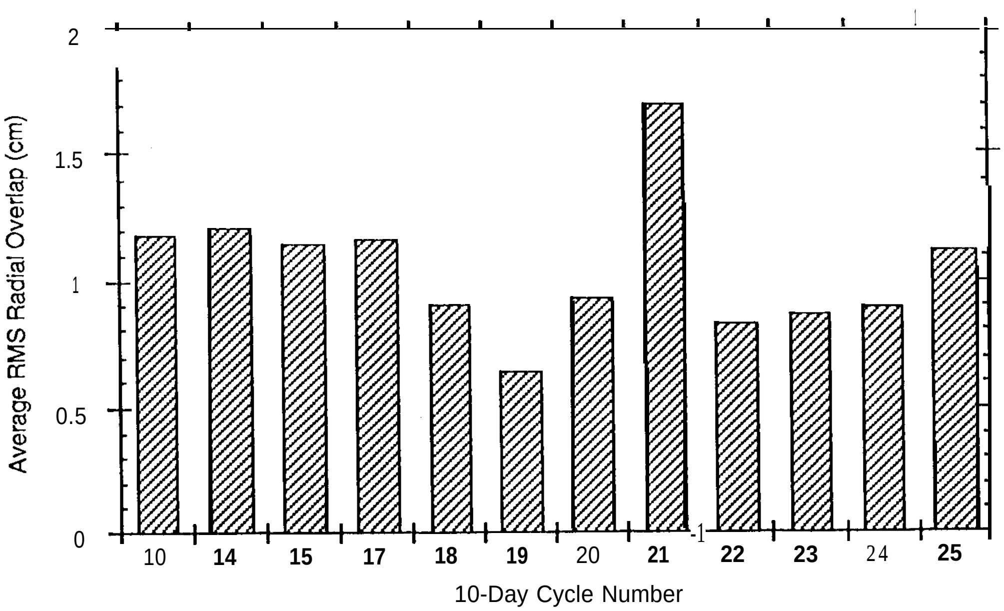


Fig. 7. TOPEX/POSEIDON radial orbit overlap for twelve complete 10-day cycles

The TOPEX/POSEIDON orbit has been determined with combined laser ranging and DORIS Doppler data by the Goddard Space Flight Center (GSFC). Fig. 8 shows the RMS differences between reduced-dynamic orbit solutions using GPS data and GSFC's dynamic orbit solutions using combined laser ranging and DORIS Doppler data over eight 10-day TOPEX/POSEIDON repeat cycles. The altitude agreements are all better than 4 cm, implying a 3 to 4 cm accuracy for

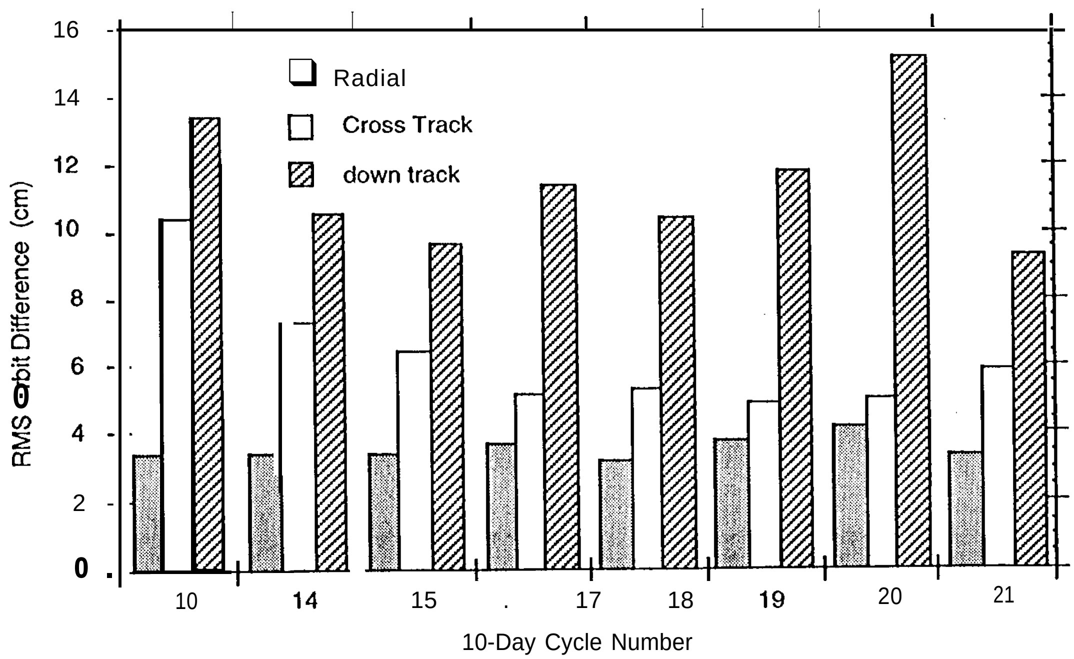


Fig. 8. **Comparison of TOPEX/POSEIDON orbit solutions with GPS against Goddard Space Flight Center laser/DORIS orbits**

TOPEX/POSEIDON altitude solutions for both GPS and laser/DORIS data types. The other two components show slightly higher differences, but still about 5 to 10 cm cross track and 9 to 16 cm down track. Since the down-track component is more sensitive to mismodeled dynamics, we believe that the reduced-dynamic TOPEX/POSEIDON orbit using GPS data has the lower error, probably less than 11 cm, in down-track direction.

SUMMARY

A **highly automated GPS data** processing system for the orbit determination of TOPEX/POSEIDON **has been** described in some detail. The estimation scenarios have been explained and the automated data processing steps described. For a typical set of data, no human intervention is required and the final results appear in the proper data base. As glitches are encountered they are analyzed in detail and the expert system is improved so that these glitches are handled automatically in the future. Using this automated processing system, the orbit of TOPEX/POSEIDON has been routinely recovered to an estimated accuracy of better than 4 cm in altitude, 6 cm cross track and 11 cm down track. These results can be obtained within two days of onboard GPS data collection. Most of the data processing for a 30-hour arc of GPS data can be performed on a single HP9000/730 workstation in less than 6 hours of CPU time.

The quality of the orbit solutions has been assessed by postfit residuals, by orbit overlap and by comparing orbits resulting from GPS tracking data with those from laser ranging and DORIS Doppler tracking data. The RMS postfit residuals on the ionospherically calibrated carrier phase observable are less than 5 mm, which is consistent with the expected value of carrier phase data noise. The RMS difference over a 4.5-hour overlap period between two 30-hour data arcs is 1 cm in altitude, 5 cm cross track and 4 cm down track. TOPEX/POSEIDON orbit solutions determined by GPS data agree with orbits determined by combined DORIS Doppler data and laser ranging data to better than 4 cm in altitude, 10 cm cross track and 16 cm down track.

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